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SAMPEX OBSERVATIONS OF GEOMAGNETICALLY TRAPPED ANOMALOUS COSMIC RAYS

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ABSTRACT

We summarize observations of trapped anomalous cosmic rays made with the Mass Spectrometer Telescope (MAST) on the polar-orbiting SAMPEX spacecraft during late 1992 and early 1993. MAST observes a trapped population of heavy ions with ≥15 MeV/nuc that includes N, O, and Ne, but very little C, located in a narrow belt at L≈2. The characteristics of this radiation belt are generally consistent with those expected from the mechanism proposed by Blake and Friesen for trapping anomalous cosmic rays in the magnetosphere and with COSMOS observations made during the last solar minimum. We discuss the location, composition, and temporal history of the trapped heavy ions observed with SAMPEX and compare them with properties of anomalous cosmic rays observed in the interplanetary medium. Although trapped He ions are also observed by MAST, it appears likely that they have a different origin.

1. Introduction

Just over two decades ago observations by the Pioneer-10 and IMP-5&7 spacecraft discovered anomalous enhancements in the quiet-time energy spectra of several elements[1,2,3] leading to the identification of a new component of cosmic rays with energies ≤50 MeV/nuc. At 1 AU the most abundant elements of this so-called "anomalous cosmic ray" (ACR) component are He, N, O, and Ne; in the outer heliosphere there is also evidence for ACR contributions to the low energy spectra of C, Ar, and perhaps H[4,5]. The ACR component is especially sensitive to the effects of solar modulation, varying in intensity by a factor of >100 over the solar cycle, and observable at 1 AU only near solar minimum[6].

Shortly after the discovery of ACRs, Fisk, Koslovsky, and Ramaty[7] proposed that they represent interstellar neutral particles that have drifted into the heliosphere, where they were ionized by solar UV or by charge exchange with the solar wind, convected into the outer heliosphere, and then accelerated to high energies (~5 to 50 MeV/nuc). Following this acceleration, now believed to take place at the solar wind termination shock[8], ACRs can propagate back into the inner heliosphere as low-energy cosmic rays. One of the key predictions of this model is that ACRs should be singly-charged, in contrast to Galactic cosmic rays, that are essentially fully stripped.

Several years later Blake and Friesen[9] (hereinafter B&F) proposed an unusual test of this model, suggesting that if ACRs are indeed singly-charged they should become trapped in Earth's magnetosphere. They reasoned that trapping could occur when a singly-charged ion with a rigidity somewhat above the geomagnetic cutoff penetrates into the magnetosphere and loses some or all of its remaining electrons in the upper atmosphere, such that its resulting rigidity is suddenly below the trapping limit. Taking into account the local geomagnetic cutoff and nominal requirements for a stably trapped population, B&F predicted[9,10] the existence of a belt of anomalous cosmic rays surrounding the Earth, located in magnetic L-shells ranging from L=2.5 to L=3.5 (the value of L refers to the distance in Earth radii from the surface of the Earth to the equatorial altitude of the appropriate magnetic field line).

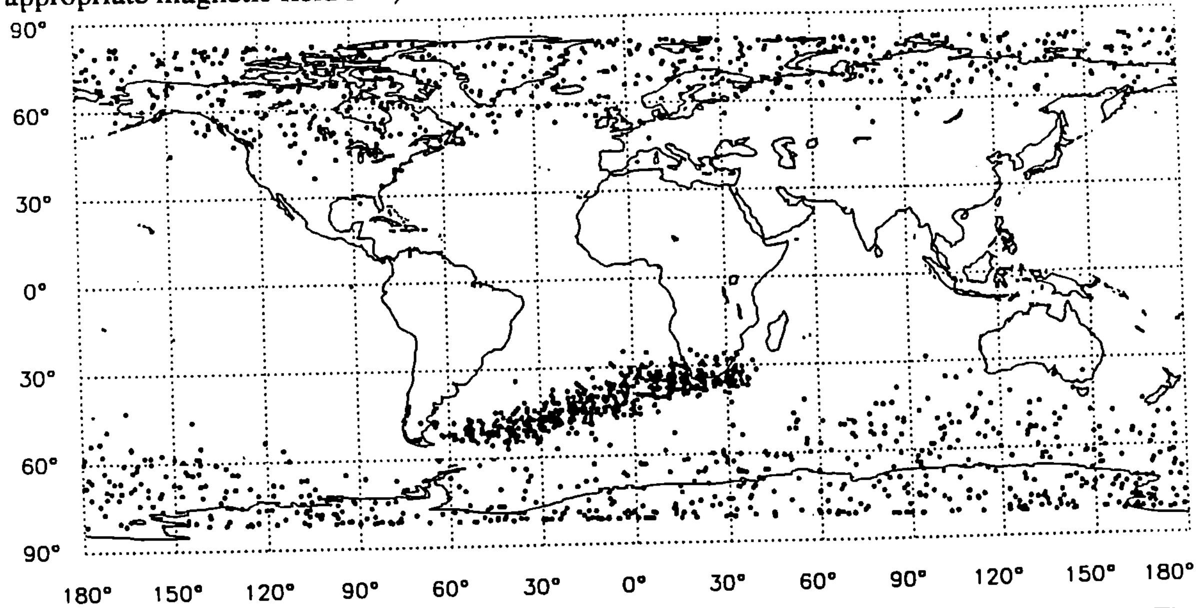

Fig. 1: The geographic distribution of observed oxygen ions with 16 to 200 MeV/nuc is indicated. The band stretching from the tip of South America to the southern tip of Africa includes O ions trapped at L=2. For comparison, note that the maximum intensity of trapped protons in the South Atlantic Anomaly (SAA) is centered approximately at 30° south latitude and 315° longitude.

At the time of the B&F paper there had been only scattered reports of trapped heavy ions with energies >10 MeV/nuc, and the composition of the trapped particles appeared to resemble solar material more than it did anomalous cosmic rays[11,12]. It was not until fourteen years later that the existence of trapped anomalous cosmic rays was verified. In the meantime, there had been a number of indirect demonstrations that anomalous cosmic rays are indeed singly-charged, culminating in more direct comparisons using the Earth's magnetic field as a magnetic rigidity filter[13].

The first evidence for trapped anomalous cosmic rays was reported by Grigorov et al.[14] from a series of flights carrying stacks of plastic track detectors on COSMOS spacecraft during the 1985 to 1988 solar minimum. Although the passive detectors on COSMOS could not measure directly the ions' spatial distribution, the orbit-averaged fluxes of ~5 to 30 MeV/nuc nuclei with Z>2 were dominated by oxygen ions with an angular distribution and temporal behavior that was generally consistent with the ACR origin proposed by B&F. These COSMOS observations are summarized in a paper in this same volume.

In this paper we summarize observations of trapped anomalous cosmic rays made on SAMPEX during late 1992 and early 1993. This paper is based on a "Highlight" talk[15] presented at the 23rd International Cosmic Ray Conference, held during July 1993, in Calgary, Canada. Since much of the material from that talk is now published elsewhere, it is only summarized here, and we direct the reader to ref. 16 for more detail.

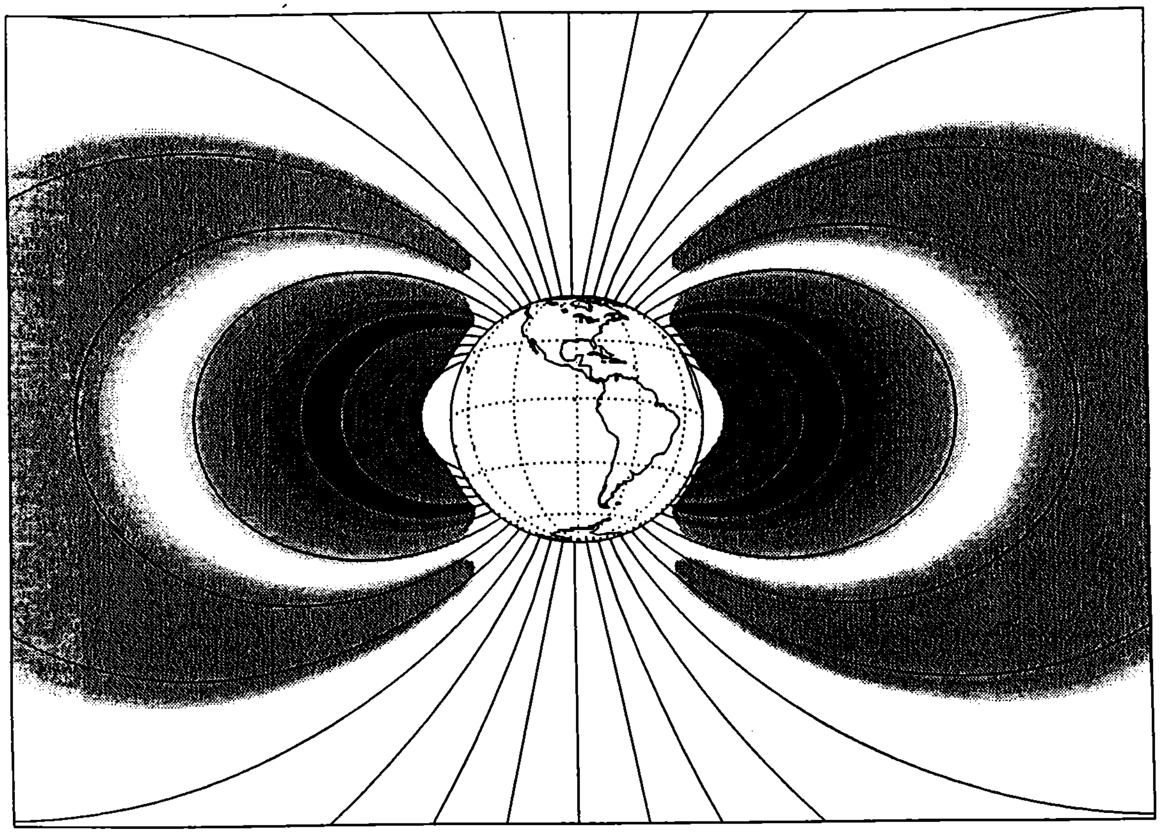

Fig. 2: A schematic representation of the location of the trapped heavy ions with $E \geq 15$ MeV/nuc in the Earth's magnetosphere. Approximate magnetic field lines are plotted each 5° in magnetic latitude. The heavy ions are located at $\Lambda \approx 45°$ ($L \approx 2$), embedded within the lower of the two Van Allen belts. Note the closest approach of the particles in the extreme South Atlantic. The figure has the magnetic axis of the Earth approximately in the plane of the page.

2. Observations

The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), the first of NASA's new line of SMEX missions[17], was launched July 3, 1992, into an 82° inclination orbit with an apogee of ~670 km and a perigee of ~520 km. It carries four instruments that measure energetic nuclei and electrons over a broad energy interval, including a Mass Spectrometer Telescope (MAST) that measures the elemental and isotopic composition of nuclei from He to Ni ($Z = 2$ to 28) over the energy range from ~15 to ~250 MeV/nuc. MAST is composed of an array of silicon solid state detectors which determine the nuclear

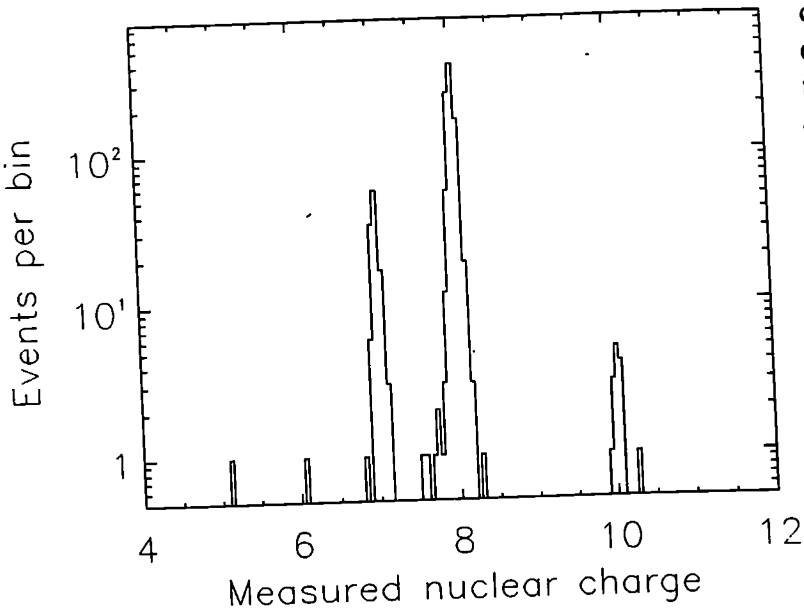

Fig. 3: Observed composition of $Z \geq 4$ nuclei at $L = 2.05 \pm 0.60$, including all days from 7/6/92 to 2/7/93 (from ref. 16). Detection thresholds in MAST range from ~14 MeV/nuc for C to ~16 MeV/nuc for O to ~18 MeV/nuc for Ne. One event with $Z = 23$ was observed.

charge, mass, kinetic energy, and trajectory of particles which stop in the detector array[18]. Although designed primarily for studies of solar flare and cosmic ray nuclei during its passage over the geomagnetic poles, MAST has also been surveying the abundances of trapped heavy nuclei since its launch.

Figure 1 shows the geographic distribution of oxygen nuclei with 16 to 200 MeV/nuc measured at SAMPEX altitude. In the polar regions SAMPEX observes Galactic cosmic rays down to a latitude where fully stripped ions are allowed by the local geomagnetic field. Penetrating to somewhat lower latitudes are singly-charged anomalous cosmic rays. The band extending from the tip of South America to the southern tip of Africa consists of anomalous cosmic rays that have become trapped in the Earth's magnetic field after losing some or all of their remaining electrons. The trapped particles approach closest to the Earth's surface in the south Atlantic region because of the offset of the Earth's magnetic dipole from the center of the Earth. Figure 2 is a schematic representation of the location of the heavy ions.

This radiation belt also includes significant abundances of N and Ne, but very little C or other elements (see Figure 3). As indicated in Figure 4, the L-shell distribution of the observed O and N ions is sharply peaked at $L \approx 2$. Although 7 to 15 MeV/nuc He is also observed in this region, it has a somewhat different L-shell distribution, also shown in Figure 4, and most likely has a different origin.

The energy spectrum of the trapped oxygen observed in this region falls off quickly with increasing energy, roughly as a steep power law in the MAST energy range. Integrating over energies ≥16 MeV/nuc, the observed abundances are $N/O \approx 0.11 \pm 0.01$, and $Ne/O \approx 0.025 \pm 0.008$. There is very little C present, $C/O < 0.004$.

3. Discussion

Both Grigorov et al.[14] and Cummings et al.[16] pointed out that the composition of the trapped ions is a key to determining their origin. Figure 5 compares the composition of several possible source populations to that observed by MAST at $L \approx 2$. The trapped composition is generally consistent with that observed for anomalous cosmic rays in interplanetary space, but not with other possible sources of magnetospheric particles. For comparison, observations of anomalous cosmic rays by MAST over the polar portions of the orbit give N/O ≈ 0.2, and Ne/O ≈ 0.1 in late 1992[19], while Voyagers 1 and 2 found C/O ≈ 0.01, N/O ≈ 0.17 and Ne/O ≈ 0.055 at ~23 AU in 1987[20].

Of those heavy elements for which ACR contributions have been observed in the outer heliosphere (He, C, N, O, Ne, and Ar) MAST has so far observed trapped populations of N, O, Ne, and possibly C. Since the relative abundance of Ar in ACRs is very small, and the Ar energy spectrum has its maximum intensity at only a few MeV/nuc[4], it is not surprising that no trapped Ar has been observed as yet (see also ref. 21). It is not expected that ACR He would be stably trapped by the B&F mechanism because the change in rigidity that occurs upon stripping is only a factor of two (compared to a factor of 8 for ACR oxygen). In addition, to reach L=1.85 would require singly-charged He ions with >300 MeV/nuc, well above the maximum energy to which ACR He has been observed in interplanetary space. It is therefore likely that the trapped He in Figure 4 has a separate origin, as suggested by its somewhat different L-shell distribution. Adams (1993)[22] and Blake (1993)[23] have independently suggested to us that the observed He may be a remnant of a solar particle population trapped during the substorm of 3/24/91 and observed by CRRES (Blake et al. 1992)[24].

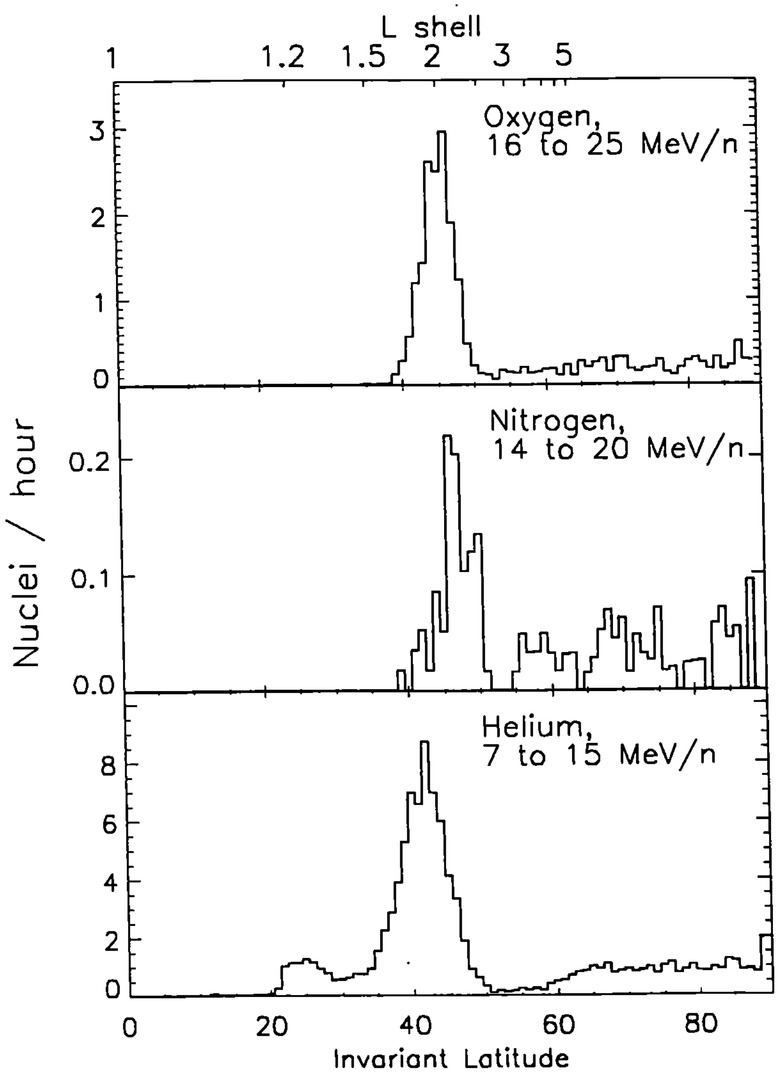

Fig. 4: Top Panel: Measured counting rates for 16 to 30 MeV/nuc oxygen ions as a function of invariant latitude (Λ). The L value is also indicated [$L = 1/\cos^2(\Lambda)$]. Only solar quiet days are included. Middle Panel: Rates for 14 to 26 MeV/nuc nitrogen ions as a function of Λ. Bottom Panel: Rates for 7 to 15 MeV/nuc He ions as a function of Λ. The smaller peak at Λ = 25° includes He in the region of the SAA.

Although the characteristics of the trapped heavy

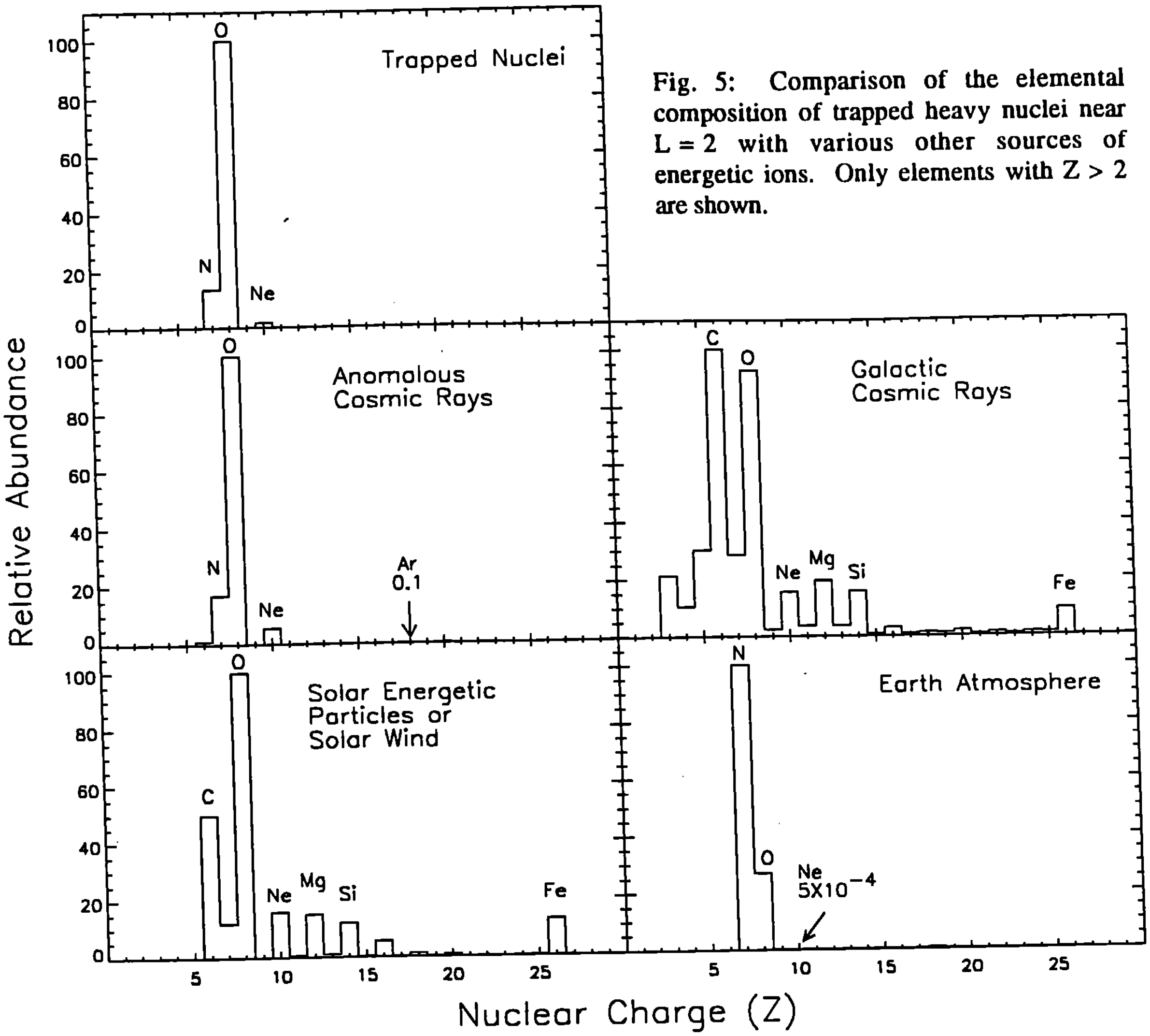

Fig. 5: Comparison of the elemental composition of trapped heavy nuclei near L = 2 with various other sources of energetic ions. Only elements with Z > 2 are shown.

ion population observed by SAMPEX are generally consistent with those expected from the B&F mechanism, there are some differences. The ACR radiation belt is located much closer to Earth (L≈2) than predicted (L=2.5 to 3.5), and it is much narrower in extent (see Figure 2). As discussed in Cummings et al.[16], these differences can be understood if the lowest energy particles that have access to a given L-shell are limited by the geomagnetic cutoff to the west for singly-charged ions (rather than the vertical cutoff assumed by B&F), and if the conditions for stable trapping are more severe than assumed by B&F. Under these conditions, we would not expect that ACR He would be trapped by the simple B&F mechanism. Tylka[21] has modeled trapped ACRs at 600 km and obtains reasonable agreement with the geographical and L-shell distributions of trapped N and O in Figures 1&2 for specific assumptions about the trapping stability.

The B&F mechanism requires an interplanetary source of singly-ionized ACR nuclei, and while it may seem surprising that there is a sufficient source of ACRs in the interplanetary medium at this phase of the solar cycle, SAMPEX observations[6,19] in the

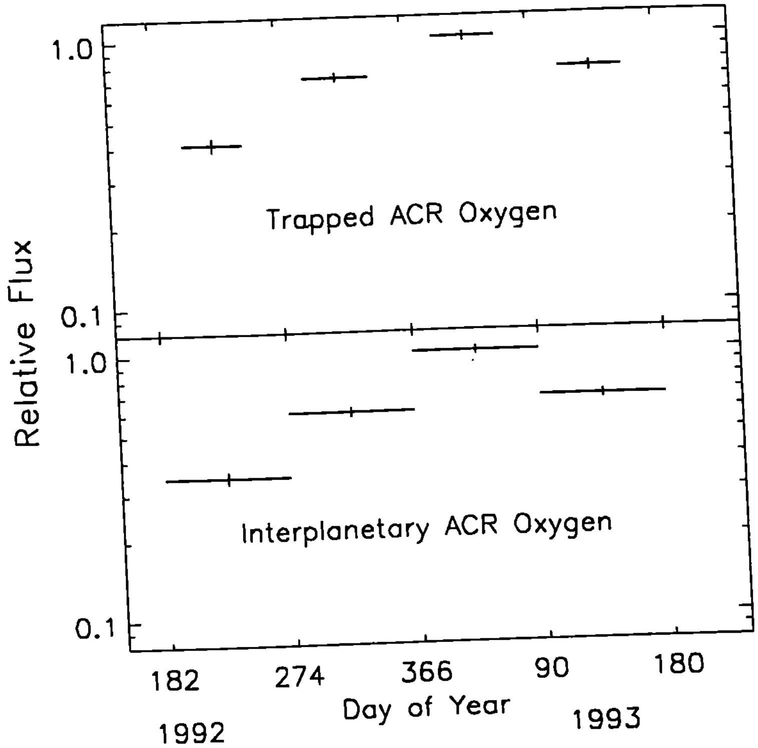

Fig. 6: Top Panel: Relative flux of trapped oxygen nuclei from 16 to 31 MeV/nuc in approximately 3-month intervals since the beginning of the SAMPEX mission. Bottom Panel: Interplanetary flux of ACR oxygen nuclei from 16 to 31 MeV/nuc measured by MAST. The interplanetary and trapped intensities are separately normalized to 1 in the third period.

polar regions of the orbit show that the interplanetary flux of ≥ 15 MeV/nuc ACRs had recovered to a significant fraction of its solar minimum level by late 1992 and that there were ACR N, O, and Ne ions in interplanetary space with kinetic energies above the geomagnetic cutoff for reaching L≈2 (assuming singly-charged ACR ions)[16]. Figure 6 shows that the change in intensity of the trapped oxygen on a time scale of a few months tracks closely the change in the interplanetary ACR flux as measured by SAMPEX (see also ref. 14). Over the course of time one would expect trapped ACRs to gradually lose energy by Coulomb drag as they mirror in the upper atmosphere near the point where they were originally stripped. This would eventually remove particles from the trapped population. The decrease of both intensities in early 1993 suggests that the storage time of the trapped fluxes is short compared to a few months (see also ref. 11). In contrast to the heavy nuclei (see Figure 6), the intensity of He nuclei has decreased a factor of ~2 over the time of the SAMPEX mission, consistent with the suggestion that it has a different origin.

In summary, COSMOS and SAMPEX observations over the past few years demonstrate that there is a sample of interstellar material trapped in the Earth's magnetosphere. While there may also be other sources of trapped heavy nuclei, it appears that ACR nuclei are the dominant component of high-energy ions with $Z > 2$ in the inner magnetosphere at the time of these observations, with an intensity at $L = 2$ that is $>10^2$ times that in interplanetary space at this time. If the intensity of trapped ACRs continues to track the interplanetary ACR intensity as it did during the 1980's[14], it may increase by a factor of ~5 as solar minimum approaches. The analysis of additional SAMPEX data should better define the distribution, composition, energy spectra, and temporal behavior of this heavy-ion radiation belt, providing additional clues to its complex history. In particular, we hope to eventually use this trapped sample of interstellar matter to study the isotopic composition of the local interstellar medium[25,26].

4. Acknowledgments

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